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Technical and economic assessment of grid-independent hybrid photovoltaic–diesel–battery power systems for commercial loads in desert environments

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Abstract

Solar photovoltaic (PV) hybrid system technology is a hot topic for R&D since it promises lot of challenges and opportunities for developed and developing countries. The Kingdom of Saudi Arabia (KSA) being endowed with fairly high degree of solar radiation is a potential candidate for deployment of PV systems for power generation. Literature indicates that commercial/residential buildings in KSA consume an estimated 10–45% of the total electric energy generated. In the present study, solar radiation data of Dhahran (East-Coast, KSA) have been analyzed to assess the techno-economic viability of utilizing hybrid PV–diesel–battery power systems to meet the load requirements of a typical commercial building (with annual electrical energy demand of 620,000 kW h). The monthly average daily solar global radiation ranges from 3.61 to 7.96 kW h/m^2. NREL's HOMER software has been used to carry out the techno-economic viability. The simulation results indicate that for a hybrid system comprising of 80 kWp PV system together with 175 kW diesel system and a battery storage of 3 h of autonomy (equivalent to 3 h of average load), the PV penetration is 26%. The cost of generating energy (COE, US$/kW h) from the above hybrid system has been found to be 0.149 $/kW h (assuming diesel fuel price of 0.1 $/L). The study exhibits that for a given hybrid configuration, the operational hours of diesel generators decrease with increase in PV capacity. The investigation also examines the effect of PV/battery penetration on COE, operational hours of diesel gensets for a given hybrid system. Emphasis has also been placed on unmet load, excess electricity generation, percentage fuel savings and reduction in carbon emissions (for different scenarios such as

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PV–diesel without storage, PV–diesel with storage, as compared to diesel-only situation), cost of PV–diesel–battery systems, COE of different hybrid systems, etc.

Keywords: Solar radiation; PV modules; Battery; Diesel generators; Commercial loads; Carbon emissions

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1. Introduction

Presently, electrical energy demand is far more greater than ever before in both developed and developing nations. The continued over-dependence on fossil fuel sources such as oil and gas (for electricity generation) is at stake because supplies are expensive, diminishing, and politically regulated. Broadly speaking, the sources of conventional means of electricity generation are finite and fast depleting. Moreover, burning of fossil fuels is the principal cause of unprecedented air pollution and environmental warming. In the wake of the above alarming issues, most nations worldwide are prompted to embark on research on solar energy (as an option to avert/mitigate impending energy crisis). The Kingdom of Saudi Arabia's (KSA) total installed electricity generation capacity of the power plants has increased phenomenally (from 1141 MW in 1975 to 27,000 MW in 2002; also the peak demand is expected to be 59000 MW in 2020) during the last 2 decades [1,2]. In particular, Dhahran's peak electricity demand has escalated from 7317 MW in year 1995 to 8332 MW in year 2001 [3,4]. The above significant increases can be attributed to rapid growth in residential, commercial, and industrial sectors. Literature reveals that commercial/residential buildings in Saudi Arabia consume an estimated 10–45% of the total electric energy consumed [1]. Due to prevailing harsh climatic conditions, the bulk of this energy (about 60%) is used by building heating, ventilation, and air-conditioning (HVAC) systems. Increased rates of electric energy consumption constitute one of the largest problems being encountered by the electric companies in the Kingdom. In order to cope with the increasing electricity consumption trends, it is imperative to explore every possible avenue for generating more energy without compromising the comfort standards [4]. One of the options to overcome this pronounced energy issue is by exploitation of indigenous renewable sources of energy such as solar energy [5]. Solar radiation intensities of geographically different provinces of Saudi Arabia are presented in Table 1. However, present work (as a case study) focuses attention on Dhahran.

Solar energy is one of the inexhaustible, site-dependent, clean (does not produce emissions that contribute to the greenhouse effect), and potential source of renewable energy options that is being pursued by a number of countries with monthly average daily

Table 1
Monthly average daily global solar radiation (W h/m^2) of different provinces (major cities) of the Kingdom of Saudi Arabia

Province (City)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Annual avg.
Eastern (Dhahran)	3790	4612	5430	6456	7323	7960	7559	7160	6512	5378	4273	3615	5839
Western (Taif)	4444	5163	5575	5819	5810	6396	6266	5929	5532	5233	4594	4383	5429
Northern (Qurayat)	3464	4736	5486	6421	7095	7418	7514	6936	6077	4741	3804	3027	5562
Southern (Abha)	4372	5275	6083	6025	6527	6459	5746	5985	6197	6433	5923	4853	5824
Central (Riyadh)	3526	4578	5073	5480	5641	6140	6125	5881	5707	5286	4503	3639	5132

Note: Data of eastern province represent average of the period 1986–93 (*Source: Meteorological Station, Research Institute, Dhahran*).
Data of other provinces represents average of the period 1971–80 (*Ref.: Saudi Arabian Solar Radiation Atlas, Riyadh, Saudi Arabia, 1983*).

solar radiation level in the range of 3–6 kW h/m^2, in an effort to reduce their dependence on fossil-based non-renewable fuels [6–13]. Solar collectors can be classified as either solar thermal energy converters or solar electric energy converters. Devices that directly convert solar into electric energy are generally called photovoltaics (PV) [11]. The concept of PV is well understood and currently (inspite of hindrances) thousands of PV-based power systems are being deployed worldwide, for providing power to small, remote, grid-independent or stand-alone applications [6]. There is a preponderance of solar energy radiation in KSA. Since Dhahran is blessed with high solar radiation level, an appreciable portion of its energy demands may be tapped from solar energy. Additionally, the use of renewable sources of energy reduces combustion of fossil fuels and the consequent CO_2 emmision, which is the principal cause of global warming. Global warming is expected to change terrain and climate of many countries unless measures are taken [14–17]. More importantly, in the light of December 1997s Kyoto's protocol on climate change (due to carbon emissions), about 160 nations have reached a first ever agreement (to turn to renewable/wind/PV power) to limit carbon emissions, which are believed to cause global warming. Although, solar energy is enormous, but PV-driven power system is still an expensive option (PV system capital cost is about 4000 $/kW, capital cost of conventional power systems is about 1000 $/kW) [18]. The high initial investment cost in PV systems is still the main road-block that hinders promotion of this technology in large-scale applications. Nonetheless, PV finds application in remote areas (where it is uneconomical to extend the utility grid) not served by an electric grid [18,19]. PV systems have the advantage of minimum maintenance and easy expansion (upsizing) to meet growing energy needs. PV modularity (modules are available off-the-shelf) is one of its major strength and it allows the users to tailor PV system capacity to the desired situation. PV systems also produce electricity during the times when we demand it most, on hot sunny days coinciding with our peak electricity consuming periods. The demerits are: PV is capital-cost-intensive and its sunshine-dependent output does not match the load on 24 h basis. However, major technological milestones (yielding cost reduction of PV, improved efficiency, etc.) may change the scenario [10,18].

Despite abundant availability of solar energy, a PV system alone cannot satisfy load on a 24-h basis [18]. Stand-alone diesel gensets (relatively inexpensive to purchase) are generally expensive to operate and maintain especially at low load levels [20]. Often, the variations of solar energy generation do not match the time distribution of the demand. Therefore power generation systems dictate the association of battery storage facility to dampen the time-distribution mismatch between the load and solar energy generation and to account for maintenance/outages of the systems [10,21]. PV-generated electricity stored in batteries can be retrieved during nights. Use of diesel system with PV-battery reduces battery storage requirement. Research carried out in other parts of the world indicate that hybrid combination of PV/diesel/battery system (represents an economically acceptable compromise between the high capital cost of PV autonomous system and high O&M + fuel cost of fossil fuel generators) is a reliable source (reliability is one of the main selling point) of electricity [19]. PV and diesel have complementary characteristics: capital cost of PV is high as compared to diesel, operating cost of PV is low (relative to diesel), maintenance requirements of PV are less as compared to diesel, diesel energy is available all the time where as availability of PV is highly dependent on solar radiation [19]. The prospects of derivation of power from hybrid PV–diesel systems has gained momentum and number of PV/diesel/battery installations exist around the world [19,22–23]. Also investments in mobilization of PV systems may stimulate the local economy (in a long-run) by making use of available local resources. The cumulative installed capacity of all solar systems around the world passed the landmark figure of 3120 MWp in 2003. The global installed capacity of solar power is expected to reach 207 GWp by 2020 (the cost of solar modules is likely to go down to US$1 per Watt delivered). Also, the projections indicate that by 2020 solar systems can provide energy to over a billion people globally and provide 2.3 million full-time jobs [24].

The research on viability of renewable energy systems at Dhahran has been the subject matter of several earlier studies [25–27]. In the present study, solar radiation data of the period 1986–93 recorded at the solar radiation and meteorological station, Dhahran (26° 32′N, 50° 13′E, East-Coast, Saudi Arabia) has been analyzed to assess the techno-economic viability of utilizing hybrid PV–diesel–battery power systems to meet the load requirements of a typical commercial building (with annual electrical energy demand of 620,000 kW h). The hybrid systems considered in the analysis consist of different combinations of PV modules (different array sizes) supplemented with battery storage system and diesel generators. The study evaluates the feasibility of utilizing solar/PV energy to meet the electricity requirements of the commercial building in conjunction with the conventional sources of electricity (diesel generators). Specifically, the merit of hybrid PV–diesel–battery system has been evaluated with regards to its size, operational requirements, cost, etc. National Renewable Energy Laboratory's (NREL) Hybrid Optimization Model for Electric Renewables (HOMER) software has been used to carry out the techno-economic viability of hybrid PV–diesel–battery power systems. HOMER is a tool or computer-model that facilitates design of stand-alone electric power systems [28]. The investigation demonstrates the impact of PV penetration on energy production, cost of energy (COE, US$/kW h), on the number of operational hours of diesel gensets for a given hybrid configuration, etc. Concurrently, emphasis has also been laid on unmet load, excess electricity generation, percentage fuel savings and reduction in carbon emissions (relative to diesel-only scenario) of different hybrid systems, cost of PV–diesel–battery systems, COE of different hybrid systems, etc.

2. Background environment and instrumentation

Climatic conditions determine the availibility and magnitude of solar energy at a site. Dhahran is located just north of the Tropic of Cancer on the eastern coastal plain of Saudi Arabia and is nearly 10 km inland from the Arabian Gulf Coast. Although it is in the vicinity of the coast, Dhahran is situated in very much a desert environment. Two distinct seasons are noticed in this region: a very hot season (May–October) and a cold season (November–April). Monthly mean temperatures reach close to 37 °C for hot months, and in cooler months the mean temperatures drop by about 20 °C as compared to the hot months. The relative humidity exhibits a large diurnal cycle on the order of 60% round the year. Typical long-term annual mean precipitation is about 80 mm. The winds blow from 270° to 360° direction range (north to north-westerly winds) for most of the time during the year [29].

The present study utilizes the data recorded at solar radiation and meteorological station (of the Center for Engineering Research, Research Institute) located at Dhahran. The instruments installed at the station meet the requirements for class 1 sensors according to the classification of the World Meteorological Organization [30,31]. The data are being recorded on hourly basis. The global solar radiation measurements are made using Eppley (model PSP) pyranometer. The station is continuously supervised to clean the sensors and to minimize instrumental problems. The sensors are regularly calibrated against reference sensors (to account for degradation and malfunctioning of sensors) maintained at the station. More description of the station and the DAS has been reported in Ref. [29].

3. Solar radiation data and operational strategy of hybrid system

Long-term monthly average daily global solar radiation values for Dhahran are plotted in Fig. 1. The radiation level is high during the summer months (May–August) as compared to other months. The yearly average daily value of the solar radiation is 5.84 kW h/m^2. Fig. 1 shows distinctly that the variation in the solar radiation values between the years is minimal. In view of the steady nature of solar radiation (and as a case study), 1993s data have been used for simulations (in HOMER). The energy calculations are made by matching the solar radiation data with the characteristics of PV modules [32]. The characteristics of some of the commercial PV modules are furnished in Table 2. The PV modules which are composed of several solar cells are integrated to form solar arrays. Despite advancements in the state-of-the-art, today's best PV systems can achieve an overall efficiency of about 12% [11]. These lower efficiency values may not make this alternative attractive at the moment. However, technological breakthroughs may change the scenario and pave way for more widespread use of PV systems [10,18].

The solar radiation varies not only during different seasons but also at different times of the day. Therefore, for applications where energy is required for a 24-h period, the need cannot be met through a PV system alone. In this connection, integration of PV installations with battery storage or diesel system or with both can meet the required load distribution on a 24-h basis. This type of coupling also avoids oversizing or undersizing of the major components of hybrid system.

The architecture of hybrid PV–diesel–battery system is shown in Fig. 2. The dispatch strategy is load-following-type. The philosophy of operation is as follows: in

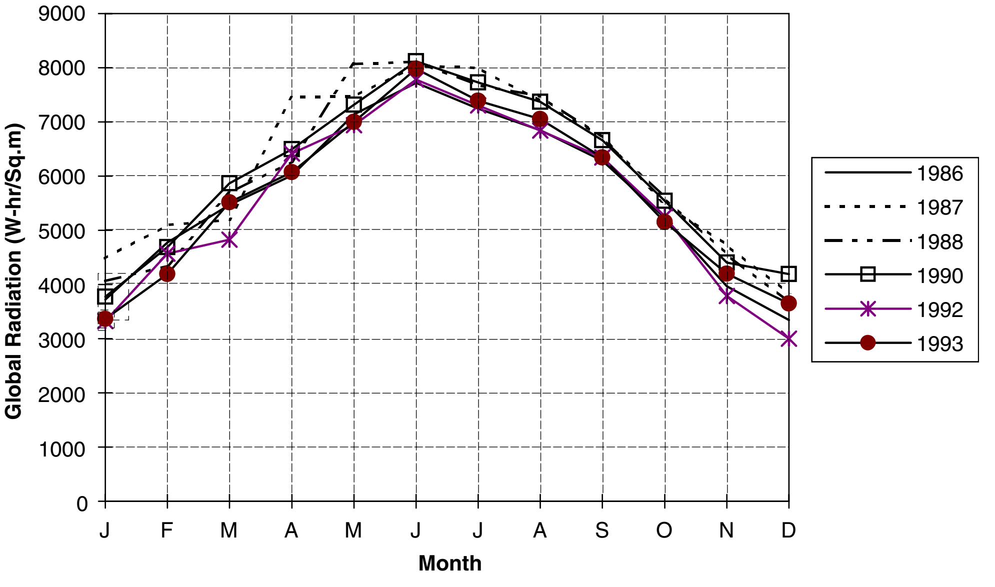


Fig. 1. Monthly average daily global radiation at Dhahran.

Table 2
Characteristics of some commercial PV modules

Module size $L \times W \times D$	Rated power (W), R_p	Current (A)	Voltage (V)	Module reference (η)
$1113 \times 502 \times 50$ (in mm)	60	3.5	17.1	0.107
$1108 \times 660 \times 50$ (in mm)	83	4.85	17.1	0.113
$18.5'' \times 25.7'' \times 2.1''$ (in inches)	35	2.33	15.0	0.15
$25.2'' \times 25.7'' \times 2.1''$ (in inches)	50	3.00	16.7	0.15
$34.1'' \times 25.7'' \times 2.2''$ (in inches)	70	4.14	16.9	0.15
$56.1'' \times 25.7'' \times 2.2''$ (in inches)	120	7.10	16.9	0.15
$50.8'' \times 39.0'' \times 1.4''$ (in inches)	167	7.2	23.2	0.15

L: length; *W*: width; *D*: depth.
The above modules are high-efficiency solar electric modules and Kyocerasolar modules.
Power specifications are at standard test conditions of: 1000 W/m^2 solar irradiance, 25° cell temperature.

normal operation, PV feeds the load demand. The excess energy (the energy above the average hourly demand; if any) from PV is stored in the battery until full capacity of the storage system is reached. The main purpose of introducing battery storage is to import or export energy depending upon the situation. In the event, that the output from PV exceeds the load demand and the battery's state of charge is maximum, then the excess energy is fed to some dump load or goes unused (due to lack of demand). A diesel system is brought-on-line at times when PV fails to satisfy the

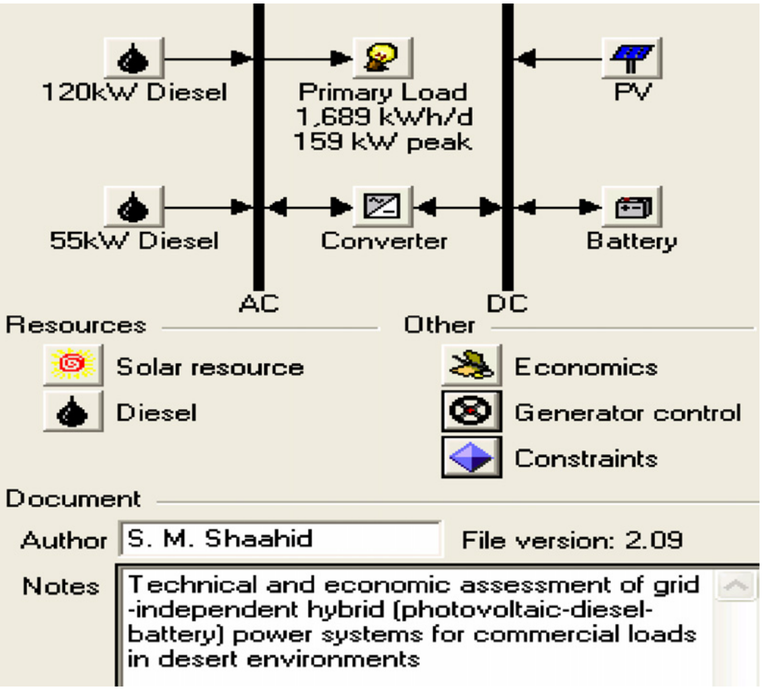


Fig. 2. Schematic of hybrid PV–diesel–battery power system.

load and when the battery storage is depleted (i.e. when the battery's state of charge is minimum).

4. Results and discussions

An important governing element of any power generating system is load. Load has substantial impact on system design. As a case study and as a representation of commercial buildings, the measured annual average electric energy consumption (based on 5 years of data) of a typical air-conditioned supermarket (located in Dhahran, floor area = 945 m^2) has been considered as yearly load (620,000 kW h) in the present study [33]. This load could also be a representation of many remotely located commercial buildings, which lack access to the utility grid (even today, there are many communities living or dwelling in small pockets in remote locations of Saudi Arabia). The daily average load profile is shown in Fig. 3. As illustrated in this figure, the load seems to peak during June–September. The peak requirements of the load dictate the system size.

In the present work, the selection and sizing of components of hybrid power system has been done using NREL's HOMER software. HOMER is a general-purpose hybrid system design software that facilitates design of electric power systems for stand-alone applications. Input information to be provided to HOMER includes electrical loads (1 year of load data), renewable resources (e.g. 1 year of solar radiation data), component technical details and costs, constraints, controls, type of dispatch strategy, etc. HOMER

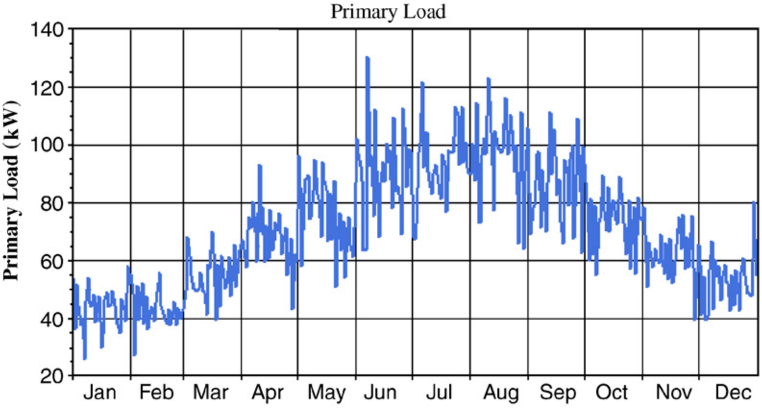


Fig. 3. Daily average load (kW) for a complete year.

designs a optimal power system to serve the desired loads. HOMER is an simplified optimization code, which performs hundreds or thousands of hourly simulations (to ensure best possible matching of supply and demand) in order to design the optimum system. It uses life cycle cost to rank order these systems. The software performs automatic sensitivity analyses to account for the sensitivity of the system design to key parameters, such as the resource availability or component costs [28].

The hybrid systems simulated in the present investigation consist of different combinations of PV modules supplemented with battery bank and diesel generators. The study explores a suitable mix of inter-dependent key parameters such as PV array power (kWp), battery storage, and diesel capacity to match the pre-defined load (with 0% capacity shortage). Diesel generators are generally sized to meet the peak demand of the power. The peak demand of the present case study is 159 kW. In this regard, two diesel generator sets with a combined power of 175 kW (to cover peak load and to cover spinning/operating reserve of about 10% to overcome rapid changes in load) have been considered for carrying out the technical and economic analysis of the hybrid systems. The capacities of the two diesel gensets (D1, D2) are 120 and 55 kW, respectively. The spinning reserve is surplus electrical generation capacity (over and above that required to cover the load) that is instantly available to cover additional loads. It provides a safety margin that helps ensure reliable electricity supply even if the load were to suddenly increase or the renewable power output were to suddenly decrease.

Several simulations for various scenarios have been made by considering different PV capacities. The PV capacity has been allowed to vary from 0 to 240 kW. The battery storage sizes (kWh) considered are 0–6 load-hours or autonomy (equivalent to 0–6 h of average load, i.e. equivalent to 0–102 Surette batteries with details as mentioned in Table 3). The study assumptions made for making simulations on HOMER are tabulated in Table 3. As a starting point, simulations have been performed for PV–diesel systems with no storage. The simulation results (*for diesel price of 0.1 US$/L*) are presented in Fig. 4. In Fig. 4, first column shows the presence of PV modules in hybrid system, second–third column indicate the presence of diesel units, fifth column highlights capacity (kW) of PV considered in a given case, 11th column shows cost of energy generation

Table 3
Technical data and study assumptions of PV, diesel units, and batteries

Description	Data
PV	
Capital cost	6900 US$/kW
Life time	25 years
Operation and maintenance cost	0 US$/year
Tilt angle PV modules	26° 32′N (latitude of Dhahran)
Diesel generator units	
Rated power of diesel unit 1 [D1]	120 kW
Minimum allowed power (min. load ratio)	30% of rated power
Capital cost	25,000 US$
Operation and maintenance cost	0.2 US$/h
No load fuel consumption	39.6 L/h
Full load fuel consumption	10.09 L/h
Overhaul period	26,280 h
Rated power of diesel unit 2 [D2]	55 kW
Minimum allowed power (min. load ratio)	30% of rated power
Capital cost	21,000 US$
Operation and maintenance cost	1.5 US$/h
No load fuel consumption	18.15 L/h
Full load fuel consumption	4.63 L/h
Overhaul period	20,000 h
Batteries	
Type of batteries	Surette 6CS25P
Nominal voltage (V)	6 V
Nominal capacity	1156 A h
State of charge (SOC)	40%
Nominal energy capacity of each battery ($VAh/1000$)	6.94 kW h
Capital cost	1200 $
Operation and maintenance cost	50 $/year
Dispatch/operating strategy:	Multiple diesel load following
Spinning reserve	
Additional online diesel capacity (to guard against increases in the load or decreases in the PV power output)	10% of the load

(COE, $US/kW h) of 1 kW h of energy, etc. It can be noticed from these results that in general the PV penetration (renewable energy fraction, column 12) has varied from 0% to 56%. In an isolated system, renewable energy contribution of 56% is considered to be high. Such a system might be very difficult to control while maintaining a stable voltage and frequency. The level of renewable energy penetration in hybrid systems (deployed around the world) is generally in the range of 11–25% [19]. A trade-off needs to be judiciously established between different feasible options. The COE from hybrid PV–diesel system (80 kW PV, 175 kW diesel system, no storage, 0% annual capacity shortage) with 25% PV fraction has been found to be 0.143 US$/kW h as shown in Fig. 4. It can be depicted from Fig. 4 that COE increases with increase in penetration of PV.

PV (kW)	D120 (kW)	D55 (kW)	Conv. (kW)	Total Capital	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	D120 (hrs)	D55 (hrs)
	120	55		$ 46,000	$ 838,110	0.087	0.00	228,024	6,801	2,534
40	120	55	60	$ 397,000	$ 1,154,714	0.120	0.13	204,490	6,032	3,126
40	120	55	120	$ 472,000	$ 1,252,216	0.130	0.13	204,490	6,032	3,126
40	120	55	180	$ 547,000	$ 1,349,718	0.140	0.13	204,490	6,032	3,126
80	120	55	60	$ 673,000	$ 1,381,174	0.143	0.25	185,282	5,341	3,623
40	120	55	240	$ 622,000	$ 1,447,220	0.150	0.13	204,490	6,032	3,126
80	120	55	120	$ 748,000	$ 1,478,208	0.153	0.25	184,982	5,341	3,623
80	120	55	180	$ 823,000	$ 1,575,710	0.164	0.25	184,982	5,341	3,623
120	120	55	60	$ 949,000	$ 1,620,976	0.168	0.35	174,095	4,868	3,809
80	120	55	240	$ 898,000	$ 1,673,212	0.174	0.25	184,982	5,341	3,623
120	120	55	120	$ 1,024,000	$ 1,706,424	0.177	0.35	170,375	4,817	3,711
120	120	55	180	$ 1,099,000	$ 1,803,926	0.187	0.35	170,375	4,817	3,711
160	120	55	60	$ 1,225,000	$ 1,875,112	0.195	0.43	167,805	4,602	3,872
120	120	55	240	$ 1,174,000	$ 1,901,428	0.197	0.35	170,375	4,817	3,711
160	120	55	120	$ 1,300,000	$ 1,936,583	0.201	0.44	159,138	4,463	3,455
160	120	55	180	$ 1,375,000	$ 2,034,085	0.211	0.44	159,137	4,463	3,455
160	120	55	240	$ 1,450,000	$ 2,131,587	0.221	0.44	159,137	4,463	3,455
200	120	55	60	$ 1,501,000	$ 2,140,156	0.222	0.49	164,285	4,469	3,920
200	120	55	120	$ 1,576,000	$ 2,177,487	0.226	0.51	151,245	4,278	3,103
200	120	55	180	$ 1,651,000	$ 2,274,379	0.236	0.51	151,149	4,278	3,090
200	120	55	240	$ 1,726,000	$ 2,371,880	0.246	0.51	151,149	4,278	3,090
240	120	55	60	$ 1,777,000	$ 2,407,182	0.250	0.53	161,707	4,353	3,957
240	120	55	120	$ 1,852,000	$ 2,429,082	0.252	0.56	145,720	4,130	2,885
240	120	55	180	$ 1,927,000	$ 2,524,216	0.262	0.56	145,353	4,130	2,835
240	120	55	240	$ 2,002,000	$ 2,621,717	0.272	0.56	145,353	4,130	2,835

Fig. 4. Technical and economic parameters of PV–diesel systems.

It is also evident from Fig. 4, that as penetration of PV increases, the operational hours of diesel generators decrease which eventually reduce emission of green house gases in the atmosphere. It can be noticed that for diesel-only situation, the operational hours of the two diesel units are 6801 and 2534, respectively. However, for PV–diesel hybrid system (80 kW PV, 175 kW diesel system, 0% annual capacity shortage, zero battery storage, as shown in Fig. 4) with 25% PV penetration, the operational hours of the two diesel units are 5341 and 3623, respectively. It is evident that the operational hours of the bigger diesel genset (120 kW) of hybrid PV–diesel system (with 25% PV penetration) decreases by 22% as compared to diesel-only situation. This indicates that introduction of PV panels has decreased load on the first diesel generator considerably. This implies that adding PV allows the system to rely more on cheaper small diesel and less on large diesel (in other words system switches to smaller diesel unit).

For a given PV capacity of 80 kW (together with 175 kW diesel system), the information related to energy generated by PV and diesel systems, excess electricity, unmet load (kWh), capacity shortage (kW h) and the cost breakdown of PV–diesel power systems is presented in Figs. 5 and 6. It can be seen from Fig. 5 that with the above system configuration, unmet load is 0 kW h and excess energy of about 3% is generated. It should be mentioned over here that this excess energy produced goes unused due to lack of demand (sometimes provision is made to provide this excess energy to dump loads). Fig. 5 indicates that monthly average hybrid PV–diesel generated power is high during summer months (May–August) as compared to other months. This is a favorable characteristic because electricity demand is high during the summer months in KSA. HOMER hybrid model indicates that the total initial capital cost of the hybrid system (80 kW PV, 175 kW diesel,

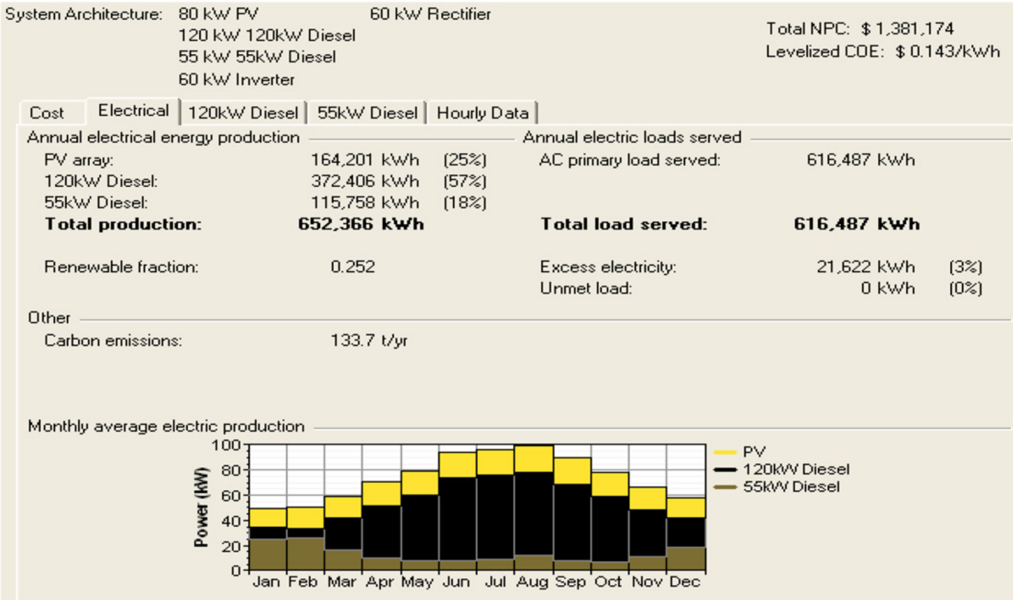
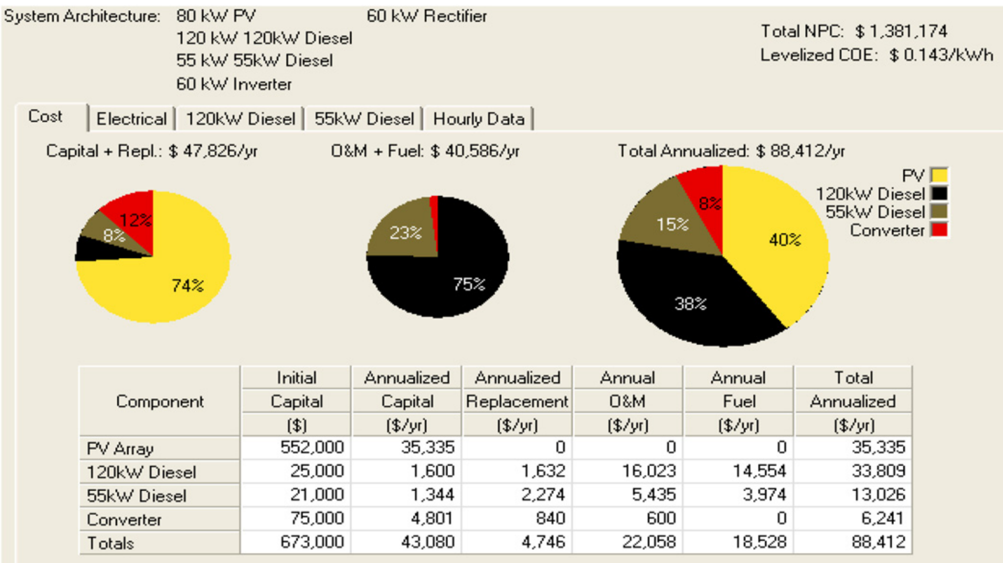


Fig. 5. Power generated by photovoltaic and diesel systems.



Component	Initial Capital ($)	Annualized Capital ($/yr)	Annualized Replacement ($/yr)	Annual O&M ($/yr)	Annual Fuel ($/yr)	Total Annualized ($/yr)
PV Array	552,000	35,335	0	0	0	35,335
120kW Diesel	25,000	1,600	1,632	16,023	14,554	33,809
55kW Diesel	21,000	1,344	2,274	5,435	3,974	13,026
Converter	75,000	4,801	840	600	0	6,241
Totals	673,000	43,080	4,746	22,058	18,528	88,412

Fig. 6. Cost of photovoltaic and diesel power systems.

no storage) is US$ 673,000 while the net present cost (NPC) is US$ 1,381,174 (Figs. 5 and 6). It can be noticed from (Fig. 6) that the intial capital cost of PV system is about 80% of the total initial capital cost. This highlights that initial cost of PV system in hybrid

system is predominant. Regarding annual operation and maintenance cost of PV and converter system, it is about 2% of the total O&M + fuel cost and the O&M + fuel cost of the diesel system is about 98%.

The percentage of fuel savings by using hybrid system (80 kW PV, 175 kW diesel system) as compared to the diesel-only situation is about 19% as shown in Fig. 4. Moreover, percentage fuel savings increases by increasing the PV capacity. The diesel fuel savings may only be quantifiable by means of justifying the additional capital expenditure invested in PV. It has also been observed that the carbon emissions for diesel-only case are 165 ton/year. However, with PV–diesel hybrid system (80 kW PV, 175 kW diesel system), the carbon emissions are 134 ton/year (Fig. 5). This reflects that the percentage decrease in carbon emissions with 25% PV penetration is about 19% as compared to diesel-only (0% PV energy) case. The effect of PV penetration on diesel operation time, diesel fuel consumption, carbon emissions, excess energy generation, etc is demonstrated more explicity in Figs. 7–9.

As a final remark, attempt has been made to explore the benefits of incorporation of short-term storage (in PV-diesel systems) in terms of fuel savings, total diesel run time, and excess energy generation relative to no-storage systems. In order to assess the impact of battery storage on a given hybrid system (80 kW PV, 175 kW diesel, 25% PV penetration), battery storage capacity was varied from 0 to 6 load-hours or autonomy (equivalent to

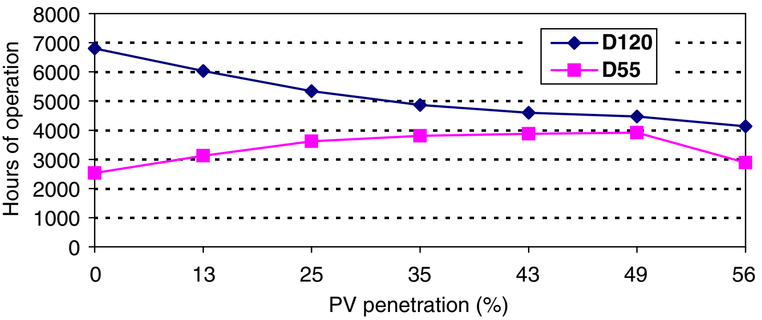


Fig. 7. Impact of PV penetration on diesel engine operation.

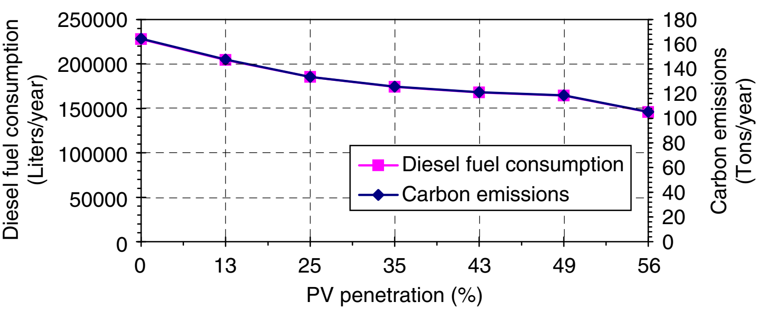


Fig. 8. Impact of PV penetration on diesel fuel consumption and carbon emissions.

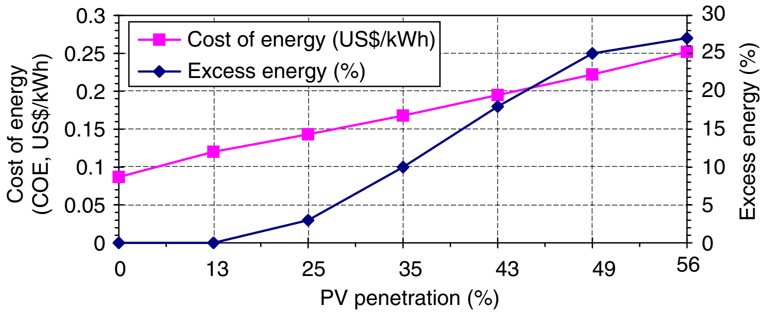


Fig. 9. Impact of PV penetration on COE and excess energy generated.

0–6 h of average load). The results of the above simulations are presented in Table 4 which demonstrates the effect of battery storage on operational hours of diesel units, diesel fuel consumption, excess energy generation, carbon emissions, COE, etc. The COE from the above hybrid PV–diesel–battery system (25% PV penetration) with 3 h of autonomy (3 h of average load) or battery storage has been found to be 0.149 $/kW h (*assuming diesel fuel price of 0.1 $/L*). Literature indicates that COE from PV systems is about 0.20 US$/kW h [34–37]. As mentioned above, percentage fuel savings by using hybrid PV–diesel system (80 kW PV, 175 kW diesel system, no storage) is 19% as compared to diesel-only situation. Expectedly, presence of battery further enhances the fuel saving potential. The percentage fuel savings for the same PV penetration is 27% (8% extra relative to PV–diesel system) with inclusion of 3 h of battery storage. Further increase in storage results in only little economic benefits because of high cost of batteries (i.e. fuel saving is not much for battery storage greater than 3 h of average load). Broadly speaking, maximum benefits of storage (in the present case) can be realized for a battery capacity of 3 h of autonomy (average load). As stated earlier, the percentage decrease in carbon emissions by using hybrid system (80 kW PV, 175 kW diesel system, no storage, 25% PV penetration) as compared to the diesel-only scenario is 19%. However, the percentage decrease in carbon emissions for the same PV penetration is 27% (as compared to diesel-only case) with inclusion of 3 h of battery storage. It can be noticed that the COE increases with increase in size of battery storage. Also, the number of operational hours (diesel run time) of the diesel units in PV–diesel system further decreases with inclusion of battery storage (Table 4). For example, for the above hybrid PV–diesel (80 kW PV, 175 kW diesel system, 25% PV penetration, no storage) system, the operational hours of the bigger diesel unit decreases by 22% as compared to diesel-only situation. However, (for the same configuration) with inclusion of 3 h of battery, the operational hours of the bigger (120 kW), diesel generator of hybrid PV–diesel (with storage) system decreases by 47% as compared to diesel-only situation. In addition to the above benefits, presence of short-term storage also results in decrease in excess energy. The excess energy is 3% for hybrid PV–diesel (80 kW PV, 175 kW diesel system, 25% PV penetration, no storage) system. However, (for the same configuration) with inclusion of 3 h of battery, the excess energy is 1% for hybrid PV–diesel–battery scenario. For a given level of PV, the lower the excess energy the better is the economics of the PV–diesel systems.

Table 4
Number of operational hours of diesel generators, PV penetration, unmet load, excess energy, annual diesel fuel consumption, cost of energy of hybrid PV–diesel systems (for given PV/diesel capacity, for different sizes of battery storage capacity, based on diesel price of 0.1 US$/L)

Hybrid system (kW)	Battery storage capacity (hours of hourly demand)	Operational hours of different diesel generators		Renewable energy (PV) fraction (% of load)	Unmet load (kW h)	Excess energy (%)	Carbon emissions (ton/year)	Annual diesel fuel consumption (L/year)	Cost of energy (COE) $/kW h
		D1 (120 kW)	D2 (55 kW)						
0 kW PV + 175 kW diesel	0	6801	2534	0	0	0	164.5	228,024	0.087
80 kW PV + 175 kW diesel	0	5341	3623	25	0	3	133.7	185,282	0.143
	1	3728	4635	26	0	2	122.6	169,847	0.140
	2	3694	4596	26	0	1	121.6	168,583	0.145
	3	3584	4638	26	0	1	120.6	167,093	0.149
	4	3501	4695	26	0	0	119.9	166,102	0.153
	5	3445	4731	26	0	0	119.4	165,480	0.158
	6	3412	4754	26	0	0	119.2	165,122	0.162

5. Conclusions and recommendations

In view of ample monthly average daily solar global radiation intensity (3.61–7.96 kW h/m^2), the study indicates that Dhahran in particular and KSA in general is a prospective candidate for deployment of photovoltaic (PV) power systems for commercial applications. The simulation results indicate that for a hybrid system comprising of 80 kWp PV system together with 175 kW diesel system and a battery storage of 3 h of autonomy (equivalent to 3 h of average load), the PV penetration is 25%. The cost of generating energy (COE) from the above hybrid PV–diesel–battery system has been found to be 0.149 US$/kW h (*assuming diesel fuel price of 0.1 $/L*). The study exhibits that for a given hybrid configuration, the number of operational hours of diesel generators decreases with increase in PV capacity. It has been found that for a given PV–diesel hybrid system, the decrease in diesel run time is further enhanced by inclusion of battery storage. The percentage fuel savings by using hybrid PV–diesel–battery system (80 kW PV, 175 kW diesel system, 3 h storage) is 27% as compared to diesel-only situation. The percentage decrease in carbon emissions by using hybrid system (80 kW PV, 175 kW diesel system, 3 h of battery, with 25% PV fraction) is 27% as compared to the diesel-only scenario. More importantly, with use of the above hybrid system, about 44 ton/year of carbon emissions can be avoided entering into the local atmosphere.

The hybrid PV–battery–diesel configuration has several advantages such as: system load can be satisfied in the optimal way; diesel efficiency can be maximized; diesel maintenance can be minimized; and a reduction in the capacities of diesel and battery (while matching the peak loads) can occur. The present investigation shows that the potential of renewable energy option of solar energy cannot be overlooked. A portion of Saudi Arabia's energy demand may be harnessed from PV systems. The observations of this investigation can be employed as a basis in designing of hybrid PV–diesel–battery systems for other locations having similar climatic and load conditions.

Over dependence on fossil fuels is alarming. Hence, investment on solar energy research is imperative to mitigate energy crisis in foreseeable future.

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